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VALIDATION AND SENSITIVITY OF A SIMULATED PHOTOGRAPH TECHNIQUE FOR VISIBILITY MODELING

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ABSTRACT

The Los Alamos Scientific Laboratory (LASL) visibility model is capable of producing simulated "before and after" pictures that illustrate visual effects of smoke plumes. Although the model has been under development for a few years, until recently there has been very little testing of the model against field experience or testing of sensitivity of the model results to numerical approximations used in the model.

Further validation and sensitivity testing of the LASL model began in late 1979. The work focused on three areas: (1) comparison of the LASL model results with plumes encountered in the field, (2) comparison of LASL background-atmosphere model results with measured sky intensities, and (3) examination of the variation of model results with changes in the numerical approximations.

The field study took place during August of 1979 in the vicinity of coal-fired power plants in northwestern New Mexico and northern Arizona. Telephotometer, NO_x plume measurements, and aerosol size distribution measurements were made in the plumes of three different coal-fired power plants. Photographs were taken of the plumes and simulated photographs were prepared by the model.

Light intensities calculated by the background radiative transfer model were compared to measured light intensities in a very clean atmosphere and in a moderately hazy atmosphere. The measured intensities were derived from photographic densities.

In addition to the field measurements, differences resulting from increased numbers of wavelengths in the color representation were examined. We also examined other changes in the numerical approximations. The results of these studies are described.

1. INTRODUCTION

With passage of the 1977 Clean Air Amendments a premium was placed on the modeling of visibility impacts associated with emissions of industrial facilities. At least three models were developed to fill the need. One of these was the LASL Visibility Model.

The LASL Visibility Model (Williams, et al.), (Champion and Williams, 1980) has been applied to a number of cases. In addition, some sensitivity studies have been performed with it (Williams, et al., 1980). However, the model has had very little validation and many aspects of the model's sensitivity have not been examined.

The limited sensitivity studies performed to date have dealt with the sensitivity of model results to model input parameters such as the viewing geometry, atmospheric stability, background visual range, wind speed, pollutant emission rates, primary particle size distribution, and secondary particle size distribution. The purpose of this work is to examine other aspects of the model's sensitivity and to describe the results of validation studies.

Specific areas examined include the use of three wavelengths of light to represent the entire visible spectrum and the sensitivity of model results to numerical approximations used within the computer codes.

The validation studies were designed to examine the model's accuracy in situations where the modeling approximations cannot be readily tested. Furthermore, the validation studies were intended to address the accuracy of the model predictions in the context of the first phase of visibility protection, that is, plume blight associated with major industrial sources.

2. THE LASL VISIBILITY MODEL

The LASL Visibility Model integrates several components to illustrate the effects of air contaminants on a vista. It can be used in either of two modes. First, if the contaminant concentrations are provided along with relevant parameters such as the size distribution of particulates, it can model the radiative transfer and provide numerical or pictorial representations of a scene subject to the contamination. Second, it may be used with emission and meteorological data to predict the chemistry, dispersion, and radiative transfer associated with the contaminant. The output of the model is in the form of a simulated photograph supplemented with various indices used to describe visibility impairment such as the blue-red ratio of the plume, plume-to-horizon-brightness ratio, and changes in chromaticity coordinates. In the simulated photograph digital information representing film densities that correspond to an original base photograph has been modified in accordance with radiative transfer calculations and depicted on film. Thus, the technique can produce "before" and "after" pictures.

Production of a simulated picture is a multi-step process. First, a photograph of the scene is taken on a relatively clean, cloudless day, at the same time a photograph is taken of a gray scale. Then, both the photograph of the scene and the photograph of the gray scale are digitized. If possible, telephotometer measurements are taken along with the picture.

From telephotometer measurements, photographic densities, or turbidity data, the background visual range for the clean scene is estimated. The background atmosphere is then simulated with a radiative transfer code based on Dave's (Braslau and Dave, 1973) iterative technique. In the model the radiance is approximated by the relation:

$$I(\tau,\mu,\phi) = \sum_{m=1}^{n} I_{j,k,m} \cos[(m-1)\phi] \qquad (1)$$

where subscript j refers to the cosine of the propagation angle μ, and subscript k refers to the layer which includes the optical depth τ. The code normally uses 20 values of μ and 10 layers. Absorption, Rayleigh scattering, and Mie scattering are considered. The background radiative transfer code also computes the phase functions for specified size distributions. In those calculations single wavelengths of 4500°A, 5500°A, and 6500°A are used to represent the colors blue, green, and red, respectively.

The solutions of the background radiative transfer problem perform a double function. First, they provide boundary conditions and forcing functions for the plume radiative transfer code. Second, they provide the link between the film densities and the calculated radiance.

The film densities must first be corrected for the distortions produced by the film. In order to do this a gray scale is photographed and digitized. The gray scale is then used to deduce a tranformation that maps the original densities onto new densities corresponding to the form,

$$D_n = \gamma \log E + C \qquad (2)$$

where E is the exposure. The transformed densities, corresponding to a portion of clean sky near where the plume is expected to appear, are compared to the radiances calculated from the background radiative transfer code. The conversion factor is

$$a = \frac{10^{-D_{ref}}}{L_{ref}} \qquad (3)$$

where D_{ref} is the density (after transformation) and L_{ref} is the radiance calculated for the same portion of the sky with the background code.

The plume radiative transfer code first computes the dispersion and chemistry of the pollutants. Dispersion is based on Pasquill Gifford (Turner, 1969) for neutral and unstable and TVA (Montgomery, et al., 1973) for slightly stable with buoyancy-enhanced dilution. The horizontal sigmas are increased by a factor of travel time to the one-fifth power with 2 minutes used for the TVA sigmas. The chemistry is based on first order kinetics with rate coefficient derived from a photochemical code for all pollutants except nitrogen dioxide. For nitrogen dioxide the concentration is given by:

$$NO_2 = \gamma(1 - \gamma)(B\,NO_2 + BO_3) + \left(\frac{NO_2}{NO_x}\right)_0 NO_x \qquad (4)$$

with $\gamma = p(x)/p(0)$

$$= \left(1 + \frac{2}{3.6\,\bar{u}t}\right)^{B+1} \qquad (5)$$

The initial oxidation and regression coefficients are both obtained from the photochemical code. Typically, the regression coefficient for neutral and unstable conditions is near 1, but is somewhat greater for stable condition, ~ 1.4.

Size distributions of secondary pollutants are also estimated from the photochemical model results.

The radiative transfer in the plume code is estimated solving the radiation transfer equation numerically with Dave's technique (Breslau and Dave, 1973) for infinite planes oriented normal to the line of sight. Numerical integration of the concentration with the appropriate scattering and absorption properties of the contaminants provides the scattering and extinction optical depths at each point along the line of sight. The result of the plume radiative transfer solution is to provide the plume transmission and the plume contribution to the radiance, L_p', for each line of sight. These parameters are then combined with the transformed film densities to produce modified film densities through the relation:

$$D_{new} = -\operatorname{Log} a\left(\frac{Tr}{a}10^{-D_{old}} + L_p'\right). \qquad (6)$$

The new densities can be displayed on a cathode-ray tube and/or photographed with a matrix camera to provide "after" pictures. The densities can also be converted to radiances and used to determine changes in chromaticity coordinates or other optical parameters.

3. TESTING OF BACKGROUND RADIATIVE TRANSFER MODULE

The testing of the background module focused on three areas. (1) the numerical approximations, (2) the adequacy of the 3-wavelength representation, and (3) a comparison between measured radiances and calculated ones. The adequacy of the 3-wavelength approximation was examined by simulating a relatively clean background atmosphere with only 3 wavelengths and with 31 wavelengths. One other objective of this endeavor was to determine the relative weights for the wavelengths of 4500 A°, 5500 A°, and 6500 A°, which would most nearly represent the chromaticity coordinates found with 31 wavelengths. With the weight chosen to duplicate the simulated horizon sky chromaticities, the chromaticity coordinates for the overhead sky were calculated with the 31-wavelength and 3-wavelength simulations. With a morning sun, the overhead is much different in color than the horizon. The x and y coordinates were .239 and .240 for the 31-wavelength representation and .242 and .240 for the 3 wavelengths represented. A similar comparison was made for the reflected spectrum from a gray body. In this case the x and y values via the 31-wavelength representation were .299 and .309, respectively, and the x and y coordinates with the 3-wavelength representation were .295 and .308, respectively.

One of numerical approximations in the background code was examined. The Fourier coefficients were increased from the normal 3 terms to 6 and finally 9. The simulations were carried out for a day with moderate haze (by Southwestern standards) on which the background visual range was only 125 km. Simulations were carried out for morning and near noon. Tables 1A and 1B report the differences found with increasing Fourier coefficient for radiances at different angles with respect to the sun.

Finally, the model simulations were compared to measured radiances on a moderately hazy day. This day was chosen because one would expect major differences between colors, with Rayleigh scattering dominating in the blue, Rayleigh and Mie scattering comparable in the green, and Mie scattering dominating in the red. Because the model gives only relative radiances, the measured and simulated values were set equal for one viewing direction and measured and simulated values were compared for other directions. The measurements

TABLE IA

RELATIVE RADIANCES (6 FOURIER COEFFS) AND % DIFFERENCE (3 COEFFS) FOR DIFFERENT ANGLES [illegible]

	i = 1		i = 2		i = 3		i = 4		i = 5		i = 6		[illegible]		[illegible]		[illegible]		[illegible]	
θ	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%
0°	1.000	9.6	.587	7.3	.361	5.3	.260	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.1	[illegible]	[illegible]	[illegible]	[illegible]
30°	.676	-2.7	.520	-2.0	.343	-1.4	.243	-0.9	[illegible]	-0.5	[illegible]	[illegible]	.110	[illegible]	[illegible]	-0.1	.080	[illegible]	[illegible]	[illegible]
60°	.601	-10.7	.376	-7.8	[illegible]	-5.3	[illegible]	-3.3	[illegible]	-1.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
90°	.411	6.9	.279	4.6	.210	2.7	.170	1.5	[illegible]	[illegible]	.124	[illegible]	.11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
120°	.411	9.0	.291	5.6	.229	3.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
150°	[illegible]	-0.9	.370	-0.6	[illegible]	0.3	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]	.14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
180°	.607	-6.5	.413	-4.2	.310	[illegible]	[illegible]	-1.9	[illegible]	-1.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE IB

RELATIVE RADIANCES (6 FOURIER COEFFS) AND % DIFFERENCES (3 COEFFS) FOR DIFFERENT ANGLES [illegible]

	i = 1		i = 2		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
θ	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%	R.I.	%
[illegible]	[illegible]	-0.4	[illegible]	0.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.549	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	-0.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE II

COMPARISON OF [illegible] RADIANCE WITH PHOTOGRAPHIC [illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	(1.0	(1.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.54	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] calculated value

were obtained with photographs with film densities transformed in accordance with Equation 2. Table II reports the results of the comparison.

For terms in excess of 6 the code experienced convergence difficulties. Presumably, these difficulties are related to the character of associated spherical harmonics of higher order. These functions undergo rapid variations with argument. Renormalization is required to properly treat higher orders of associated spherical harmonics. Renormalization has not been used in the code.

Tables IA and IB show the differences found in increasing Fourier coefficients for radiance at different azimuth elevation angles and azimuth angles with respect to the sun. Table IA shows the greatest variation in the relative radiances for the six and three Fourier coefficients calculated. The differences are greater at low observation angles, that is, low values of θ. The differences are smaller as the value of μ increases. This means that, at low observation angles, when the sun is low, scattering is more anisotropic and the plane-parallel layer approximation is least accurate. Thus, more Fourier coefficients may be required.

Table IB was chosen because it represents the least variation in the relative radiances. The values calculated for the three coefficients are practically equal, even for low observation angles, for example, small μ. This shows that near noon scattering is more isotropic. Three Fourier coefficients are sufficient for the calculation of the radiances.

3.1 Testing of the Plume Model Predictions

During August of 1979, a brief field program was carried out to test the model's predictive capability. An aircraft with low-speed capability was used to sample smoke plumes and to provide a platform for plume photography. The aircraft carried instruments for measuring total oxides of nitrogen, particulate concentrations, and condensation nuclei. The particulate measuring device was a quartz crystal monitor (QCM) with aerodynamic size-segregating capability (Fowler and Sedlacek, 1979). Supporting photography and telephotometer measurements were made on the ground.

Sampling was carried out in the plumes of three Southwestern power plants. These included a large plant burning high-ash coal with relatively inefficient particulate collectors (Plant A); a smaller plant with efficient particulate collectors and sulfur oxides scrubbing (Plant B); and a large plant burning moderate-ash coal with efficient particulate collectors and no sulfur oxide controls (Plant C). All plants burned low-to-moderate sulfur coal.

During the sampling period relatively windy conditions were encountered; however, a number of interesting cases suitable for simulation were found. From the complete set of photographs six were chosen for simulation. The meteorological, plant, and viewing conditions for the six cases are described in Table III with more details provided in Table A-I in the Appendix.

The photo CRSJ 831 deserves special mention. In this case, the plume from the small plant was approximately 350 meters higher than that from the large, despite the fact that the two plants were less than 15 kilometers apart and the stack tops differed in elevation by only 30 meters. The winds were moving the plume from the large plant to the north toward the small plant site, but the plume from the small plant was traveling east in what appeared to be a lighter wind. In this case, the plume rise module would not predict the actual plume height, and an artificially high stack height was used to provide the proper plume elevation.

Wind speeds near Plant C were based on pibals provided by the plant operator whereas wind speeds near Plant A were based on timed upwind and downwind passes over ground features with air-speeds of 60 mph or less. Wind directions were based on plume travel directions. Atmospheric stability was estimated from the aircraft measurements of the vertical temperature distribution for stable conditions or from the Turner categorization (Turner, 1969) scheme for neutral or unstable conditions using extrapolated 10-meter-height winds. Size distributions for

TABLE III

METEOROLOGICAL, VIEWING, AND PLANT CONDITIONS FOR THE SIMULATED SCENES

Photograph	Date	Distance from Plant	Plant	Viewing Angle	Wind Speed and Height	Stability	Case
1 - 4B	8/27/79	8 km	A-1+	cross plume	8 m/sec	C	CRP 827
1B	8/28/79	24 km	C-3	upwind to quarterly upward	6.1	E	CRP 27
2B	8/28/79	24 km	C-3		6.1	E	CRP 27
3B	8/28/79	40	C-3	quartering to near cross-wind	6.1	E	CRP 210
5B	8/31/79	40	B-1	upwind	1.0	E	CRSJ 831
	8/31/79	8	A-1+	crosswind	3.0	E	CRF 831

the plume particulates were based on the QCM measurements. In the case of Plant B, the plume aerosols were not significantly elevated above background. In the case of Plant C, the elevated particulate concentrations were only found very near the plant. For Plant A, aerosol concentrations were greatly elevated; however, the size distributions seemed to be variable from one pass to another.

In three cases, photographs with similar terrain and similar viewing angles were available without perceptible plumes. In these cases CRRP 827, CRRP 831 and CRSJ 831, the cleaner nearby photographs (taken on the far side of the plume or after it had dispersed), could be used as base photographs. However, in the case of photographs 2-6, 2-7, and 2-10, there were no suitable base photographs available. In these cases, the plume photographs were artificially cleaned up to provide new base photographs. This was accomplished by determining the perceptible outlines of the plumes and then either extrapolating clean sky from above the plume down to the ground or by interpolating between clean sky above and below the plume if the plume were above the ground. One potential difficulty in this approach is that in the two upwind-looking cases, the plume calculations suggest that the plume influences the radiances for portions of the sky above the perceptible plume. In this circumstance, the plume radiances change slowly with angle, leaving the viewer without perceptible boundaries. The more rapid changes near the horizon are perceptible and leave the viewer with the impression that the plume influences a much smaller portion of sky than it in fact does.

Photographs 1A through 5A are points made by digitizing the original slides, correcting the digital information based on measurements of a photographed gray scale, and photographing the cathode-ray tube with a matrix camera with Vericolor 4 x 5 sheet film. Photographs 1B through 5B are simulated photographs made with the matrix camera on Vericolor 4 x 5 sheet film.

In addition to the qualitative comparison a quantitative comparison was also made. The quantitative comparison was made by comparing the color contrast between the perceptible plumes and the sky above them for three azimuth angles for each photograph. The color contrast was defined as:

$$C_c = \sqrt{\left(\frac{L_{PB} - L_{SB}}{L_{SB}}\right)^2 + \left(\frac{L_{PG} - L_{SG}}{L_{SG}}\right)^2 + \left(\frac{L_{PR} - L_{SR}}{L_{SR}}\right)^2} .$$

The radiances L_{PB}, L_{SB}, etc. were obtained from the transformed film densities. The color contrasts were measured on the displayed real plumes and the displayed simulated plumes separately and compared for the same azimuth angles. In this case, the elevation angles of the sky and plume were not necessarily the same. Measurement of radiances were also made for the same angles in cases where the same base photographs were used. Table A-2 in the Appendix reports the measured radiances. Table IV reports the first comparison.

One difficulty in this approach is similar to that discussed earlier, that is, in the upwind looking cases the top of the plume is not sharply defined and much of the sky above the perceptible plume may be influenced by the plume.

In the case of three of the photographs, all associated with Plant C emissions there is qualitative agreement between the simulations and the photographs. For one of the other photographs the simulation is poor (CRP 831, which is not shown). In this instance, the model would be expected to fail because the plume is optically thick for downward traveling light. The model assumptions permit optically thick plumes along the line of sight as long as the plume is optically thin to direct sunlight. In this case, the prominent shadow observed below the plume is a clear indication that the plume is optically thick to direct sunlight. Thus, the failure of the model in this instance is to be expected. In two other instances, there appears to be some difference between the model predictions and the observed plumes. In one case, the particulates appear to be a little more obvious in the simulation than in the observed plume. The differences in this case might be traceable to the differences between actual emissions and assumed emissions. Assumed emissions were based on 95% control while the equipment has operated at efficiencies as

TABLE IV

COMPARISON OF BLUE-RED RATIOS NET COLOR CONTRASTS MEASURED AND CALCULATED

	Right-hand side of picture		Center		Left-hand side of picture	
Cases	B/R	CC	B/R	CC	B/R	CC
CRP 26	.673	.278	1.06	.184	.73	.24
SP 26	.522	.526	.96	.229	.67	.30
CRP 27	.674	.279	.475	.66	.60	.690
SP 27	.544	.449	.442	.71	.67	.790
CRP 210	.534	.454	.453	.543	.567	.416
SP 210	.728	.235	.586	.386	.724	.383
CRSJ 83	.588	.438	.576	.484	.502	.56
SPSJ 83	.415	.641	.140	1.09	.407	.563

high as 98% and seems to exhibit test-to-test variations in emissions.

Finally, in one case, CRSJ 832, the simulated photograph depicted a plume with less width and more density in its central core. This was a down-axis case with light winds where wind meander would be important. The code used a simple $t^{.2}$ law for converting short-term sigmas into long-term values. Larger sigmas would lead to plumes comparable to the one observed.

Four of the cases were analyzed to determine blue-red ratios and color contrast between the plume and the sky above or below. Table III reports the values of the parameter. The positions and radiances found are reported in the Appendix. Generally, the code seems to tend to a slight overprediction. However, this may be misleading because the larger plume depths, of the simulated plumes apparent on the photos, meant that the comparisons were between different portions of the sky. It also appears that the parameters chosen do not provide a very good depiction of the perceptibility of plumes. For example, in two source instances the actual plumes are more evident than the simulated ones, although the parameters would suggest otherwise.

Some of the discrepancy between the real plumes and the predicted ones may be the result of an overprediction of the dispersion. Such an overprediction would lead to more diffuse, less evident plumes, although the greater mixing would lead to a greater fractional conversion of nitric oxide to nitrogen dioxide. Higher conversion rates would lead to lower blue-red ratios and higher color contrasts.

4. CONCLUSIONS

The LASL visibility code has been tested against actual plumes under a number of different circumstances. Qualitatively the simulations seem to provide reasonable representation of the actual plumes. However, it does appear that in some cases the simulated plumes are more diffuse than the actual plumes with the result that the simulated plumes are less apparent. Furthermore, visibility parameters suggest some overestimates of the plumes' appearance. These two circumstances would be consistent with overprediction of dispersion.

In two cases, the model performed less well. In one instance, the simulation for a plume with very high particulate concentrations appeared much too bright. In this instance, the plume was seen to have an obvious shadow which indicates that the plume was optically thick to direct sunlight. The model is currently not suited to do the predictions for a plume which is optically thick to sunlight.

These studies suggest a need for further validation work wherein the emission parameters are well known and the dispersion is well defined over short test periods. There is also a need to examine meander of winds during stable conditions. Finally, it appears that the present stable of visibility parameters is not adequate to describe perceptibility of smoke plumes.

L([illegible]) - Radiance as a function of [illegible], [illegible] and [illegible].

$L_{j,k,m}$ - Radiance for the j propagation angle, kth layer and mth Fourier coefficient.

D_n - Transformed film density.

E - Exposure of film grain.

a - Factor for conversion of calculated radiance to film exposure.

D_{ref} - Film density used to obtain a.

L_{ref} - Calculated radiance corresponding to D_{ref}.

NO_2 - Nitrogen dioxide concentration.

ε - Regression coefficient for calculation of NO_2.

σ - Dilution factor for traveling from 2 km in the plume to distance x.

BO_3 - Background ozone concentration.

BNO_2 - Background nitrogen dioxide concentration.

$\left(\frac{NO_2}{NO_x}\right)_i$ - fraction of NO_x converted by thermal oxidation before plume height stabilization.

NO_x - Plume oxides of nitrogen concentration.

$\chi_p(x)$ - Plume concentration of conservative species of downwind distance of x.

$\chi_p(L)$ - Plume concentration of conservative species at 2 km downwind.

B - Exponent of distance in the power law expression for the vertical dispersion parameter.

D - Exponent of distance in the power law expression for the horizontal dispersion parameter.

u - Wind speed.

t - travel time in hours.

D_{new} - Calculated modified film density.

Tr - fractional transmission along the line of sight.

Bold - Original film density.

L_p - Plume radiance.

C_c - Color contrast.

L_{pB} - Plume radiance for color blue.

L_{SB} - Sky radiance for color blue.

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APPENDIX A

TABLE A-I

SUMMARY OF PARAMETERS USED IN SIMULATION

Case	Camera Field of View	Wind Direction	Wind Speed	Compass Bearing From Observer to Plant	Distance to Plant	Stability	Particulate Emission Rate	NO2 Emission Rate	Fly Ash MMD
[illegible]	[illegible]	250°	6.1 m/sec	244	24 km	TVA stable	[illegible] g/sec	[illegible] g/sec	[illegible]
[illegible]	[illegible]	250°	6.1 m/sec	244.	[illegible] km	TVA stable	[illegible] g/sec	[illegible] g/sec	[illegible]
[illegible]	[illegible]	250°	6.1 m/sec	25[illegible]	4[illegible] km	TVA stable	[illegible] g/sec	[illegible] g/sec	[illegible]
[illegible]	[illegible]-284	170°	3.[illegible] m/sec	[illegible]	8. km	TVA stable	8[illegible] g/sec	9[illegible] g/sec	[illegible]
[illegible]	[illegible]-54	314°	[illegible] m/sec	4[illegible].	[illegible] km	Turner C stable	8[illegible] g/sec	9[illegible] g/sec	[illegible]
[illegible]	[illegible]	2[illegible]°	1 m/sec	2[illegible].	4. km	TVA stable	[illegible] g/sec	14 g/sec	[illegible]

TABLE A-II

MEASURED AND SIMULATED PLUME RADIANCE

	BKG				CENTER				LAST			
Case	Pixel, Line	B	G	R	Pixel, Line	B	G	R	Pixel, Line	B	G	R
[illegible]	[illegible] [illegible] [illegible]	[illegible] .216 .240	.254 .241 .257	.269 .256 .238	[illegible], 196 20[illegible], 175*	[illegible] .130	.228 .229	.269 .275	20, 165* 20, 145E 20, 175	.149 .171 .16[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.164 .19[illegible] [illegible]	.203 .236 .246	.265 .24[illegible] .15[illegible]	[illegible], 196 20[illegible], 17[illegible]* 20[illegible], 14[illegible]	.214 .19[illegible] [illegible]	.256 [illegible] [illegible]	.249 [illegible] [illegible]	20, 184 20, 164* [illegible], 14[illegible] [illegible]	.164 .14[illegible] .24[illegible] [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible] .14[illegible] .24	.268 .219 .247	[illegible] [illegible] .19[illegible]	3[illegible], 204 3[illegible], 17[illegible]* 3[illegible], 146B	.24[illegible] [illegible] .251	[illegible] [illegible] .212	[illegible] [illegible] .14[illegible]	[illegible] 8, 1[illegible]* 8, 11[illegible]E	[illegible] [illegible] .144	[illegible] [illegible] .20[illegible]	[illegible]
[illegible]	[illegible]	[illegible] [illegible] .244	.240 .238 .244	.241 .24[illegible] .181	3[illegible], 204 3[illegible], 1[illegible]* 3[illegible], 146B	.210 .21[illegible] .301	.305 .24[illegible] .20[illegible]	[illegible] .230 .14[illegible]	1[illegible], 11[illegible]E 1[illegible], 16[illegible]* 9, 20[illegible]	.16[illegible] .19[illegible] [illegible]	[illegible]	[illegible]
[illegible]	[illegible]* [illegible], 14[illegible]E	[illegible] .27[illegible]	.244 .261	.245 .183	276, 181* 276, 146B	.159 .272	.206 .250	.246 .192	165, 18[illegible]* 165, 146B	.196 .261	[illegible] .22[illegible]	.149 .149
[illegible]	[illegible]* [illegible], 14[illegible]	[illegible] .26[illegible]	[illegible] .270	.26[illegible] .210	[illegible], 181* [illegible], 146B	.21[illegible] .301	.24[illegible] [illegible]	[illegible] .190	16[illegible], 1[illegible]* 166, 146B	[illegible]	.219 .209	[illegible]
[illegible]	466, [illegible] 4[illegible], 190* 4[illegible], [illegible]	.0369 [illegible] .03[illegible]	.029 .0282 .0355	[illegible] .0269 .02[illegible]	264, 208 264, 190* 264, 180	.0469 .0330 .069[illegible]	.051[illegible] .0490 .06[illegible]	.04[illegible]9 .04[illegible] .0469	104, 20[illegible]* 10[illegible], 1[illegible]0E	.01[illegible] .0602	.04[illegible] .06[illegible]	[illegible] .04[illegible]
[illegible]	4[illegible], [illegible] 4[illegible], [illegible]* 4[illegible], 1[illegible] 4[illegible], 1[illegible]	.02[illegible] [illegible] [illegible] .0105	.0245 .0295 .0264 .02[illegible]9	.0253 .025[illegible] .02[illegible] .0130	264, 220 264, 200* 264, 184 264, 146E	.0330 .0350 [illegible] [illegible]	.03[illegible]1 [illegible] [illegible] [illegible]	.0416 .0436 .041[illegible] [illegible]	10[illegible], 164B 10[illegible], 1[illegible] 1[illegible], [illegible]* 1[illegible], [illegible]	.06[illegible]6 [illegible] .0164 .01[illegible]	.04[illegible] [illegible] [illegible] [illegible]	[illegible]

* Denotes plume

B Denotes background